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ENERGY AND EXERGY PERFORMANCE OF THREE FPSO OPERATIONAL MODES

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Abstract. Floating, Production, Storage and Offloading (FPSO) is a floating facility used in primary petroleum processing. In Brazil, most FPSOs have been installed in Campos Basin and new facilities may be implemented in the pre-salt area are projected to boost the Brazilian oil production. Crude oil composition has a significant influence on the operational mode of the FPSO. In this study, three operational modes of a FPSO are assessed: the first mode is used when the crude oil has the maximum water and CO₂ contents, the second mode is implemented for a composition of 50% basic sediment and water (BSW) in the crude oil, and the third mode is operated when the crude oil has the maximum oil and gas fractions. The FPSO facility configuration changes with the operational mode, and it is possible to have gas export, gas injection, and CO₂ injection, in order to achieve the functional conditions established by the FPSO operator. Energy and exergy criteria have been applied to evaluate and compare the performance of components and systems of the three operational modes of the FPSO. The processing and utilities plants have been modeled and simulated by using Aspen HYSYS®. Results indicate that higher oil content in the crude oil increases the power consumption, the exergy requirement and the destroyed exergy of the FPSO.

Keywords: FPSO, energy performance, exergy performance, operational mode

1. INTRODUCTION

FPSOs have experienced positive trends in the primary petroleum industry. In Brazil, FPSOs have a high impact in oil production operations, particularly in the Campos Basin, where several facilities have been installed and will be implemented in the future. FPSO operations are energy-intensive processes, therefore the oil and gas industry is interested in the research and development of projects that would decrease the energy use and environmental impact of these offshore operations, thus enhancing their sustainability. The analysis and the use of energy and energy efficiency tools in the offshore industry provides an essential framework for the implementation of energy management systems (International association of oil and gas producers and The global oil and gas industry association for environmental and social issues 2013).

A FPSO must be able to operate under a variety of process conditions. The composition of the crude oil is a variable that defines the operational mode of the FPSO studied in this paper. Different operational modes imply changes in the processes and in the energy requirements of the FPSO. Conducting an energy analysis, which is based on the First Law of Thermodynamics, gives information about the distribution of the energy use in the FPSO. However, performing an exergy analysis, which is based on the First and Second Laws of Thermodynamics, shows the irreversibility sources,

and this may help identifying improvement potentials for the FPSO processes and systems. FPSO energy and exergy analyses provide an understanding of the energy and exergy behavior of the plant and its processes.

Exergy analyses in the offshore industry were performed by Oliveira and Van Hombeeck (Oliveira Jr and Van Hombeeck 1997), Nguyen et al. (T. Van Nguyen et al. 2013; T.-V. Nguyen et al. 2014), Voldsund et al. (Voldsund, Nguyen, et al. 2013; Voldsund, Ertesvåg, et al. 2013; Voldsund et al. 2014), and Carranza and Oliveira (Carranza Sánchez and Oliveira Jr 2015a), but these analyses were applied to fixed offshore platforms. This work is focused to the energy and exergy analyses of the FPSO offshore facility, and preliminary works related to exergy analysis of a FPSO were carried out by Barrera et al. (Barrera and Bazzo 2013; Barrera, Bazzo, and Kami 2015) and Carranza and Oliveira (Carranza Sánchez and Oliveira Jr 2015b).

The aim of this paper is to apply energy and exergy analyses to a FPSO in order to assess the performance and understand the distribution of the energy and exergy consumption in the systems of a FPSO operating in three operational modes. This work is divided as follows: in Section 2, a description of the FPSO operational modes is given; in Section 3, a brief description of energy and exergy concepts is showed; and in Section 4, the results are presented and discussed.

2. FPSO OPERATIONAL MODES OVERVIEW AND SIMULATION

Figures 1, 2 and 3 show the simplified schemes of the FPSO processes in operational modes 1, 2 and 3, respectively. Lines in gray indicate that the stream is disabled. In the *Separation train*, the crude oil is separated into oil, gas and water. Dilution water is used to improve the oil purity. Gas from the first separation stage is sent to the *Main compressors A (MC-A)*, while gas from the final separation stage is sent to the *Vapor recovery unit VRU* where it is compressed and transferred to the *MC-A*. Gas compressed in the *MC-A* is dehydrated in the *Gas dehydration unit (GDU)*. Dehydrated gas has several treatments and can be used in different ways, depending on the crude oil composition. In this paper, three compositions, supplied by the FPSO operator, have been considered: 1) in the *maximum water/CO₂* composition, the crude oil has the highest water and CO₂ contents, and it is used to characterize the end-life of the crude oil reservoir, 2) in the *50% BSW* composition, the crude oil contains about half of water, and it is used to represent the middle-age of the reservoir, and 3) in the *maximum oil/gas* composition, the crude oil has the highest quantity of oil and gas, and it is used to characterize the first stage of the oilfield production. Each composition is associated to one operational mode.

In the operational mode 1 (maximum water/CO₂) all gas is injected, see Fig. 1, the dehydrated gas bypasses the *CO₂ membrane unit* and is directly sent to the *Main compressor B (MC-B)* and after to the *Combined compressors (CC)* to reach the pressure required for injection purposes. The fuel gas for the *Gas turbine (GT)* is imported from an external supplier. In the operational mode 2 (50% BSW), see Fig. 2, a fraction of the dehydrated gas is sent to the *CO₂ membrane*, while the remaining gas is processed directly through a section of the *MC-B*, and then to a section of the *CC* for further compression and injection in the wells. The treated gas in the *CO₂ membrane* is mainly used for export purposes and a slight quantity is used as fuel gas in the *GT*. Gas to export is compressed in a section of the *MC-B* and in a section of the *CC*. The CO₂ recovered from the membrane unit is compressed in the *CO₂ compressors* and in a section of the *CC* in order to be injected into the well. In the operational mode 3 (maximum oil/gas content), see Fig. 3, all dehydrated gas is treated in the *CO₂ membrane* in order to be exported, except for the part used as fuel for the *GT*. The separated gas is compressed in the *MC-B* and in a section of the *CC* for export purposes. Separated CO₂ is compressed in *CO₂ compressors* and in a section of the *CC* to be injected.

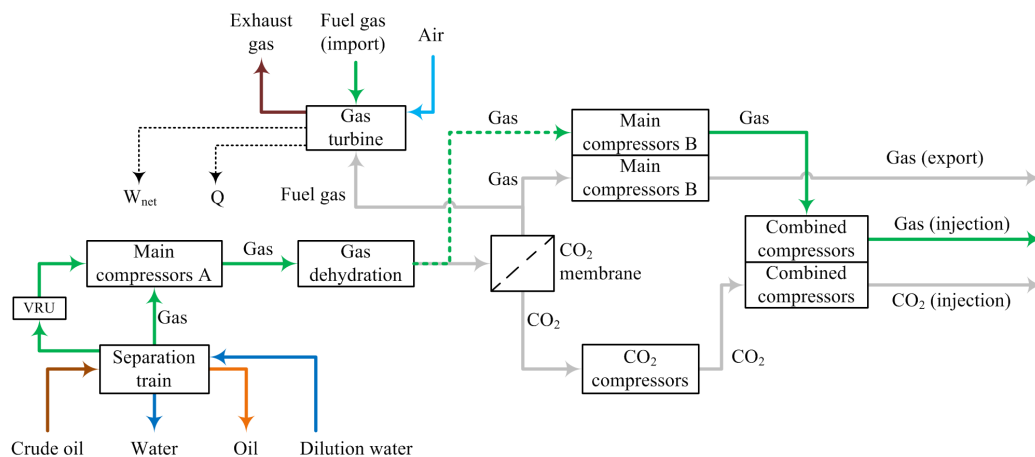


Figure 1. Simplified scheme of the operational mode 1 (maximum water/CO₂)

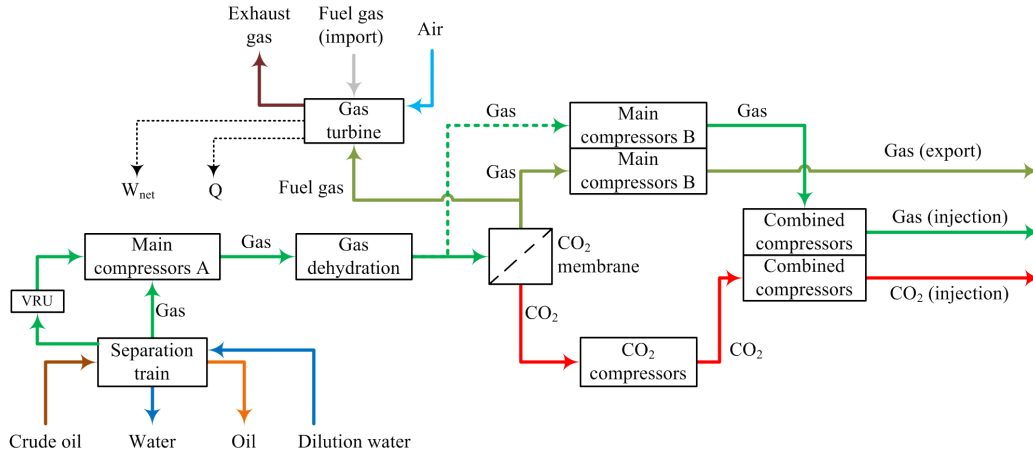


Figure 2. Simplified scheme of the operational mode 2 (50% BSW)

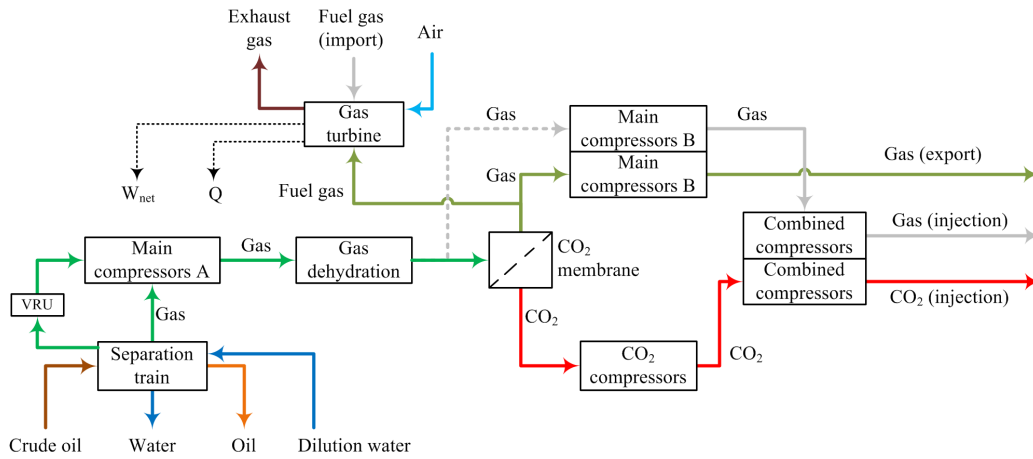


Figure 3. Simplified scheme of the operational mode 3 (maximum oil/gas)

Modeling and simulations were performed in Aspen HYSYS® (Aspen Technology Inc. 2012) and the following assumptions were made:

- Simulations were performed assuming the same crude mass flow rate for the three operational modes.
- 0.8%, 2.0% and 4.0% of the crude oil mass flow rate were considered for dilution water in the mode 1, 2 and 3, respectively.
- 50% of the gas is bypassed and the other 50% is sent to the CO_2 membrane in mode 2.
- Processes of injection of water in wells and desalting by dilution water were not considered.
- Separation efficiencies of the dehydration and CO_2 membrane processes were assumed as 100%.
- Friction losses in compressors were disregarded.

3. THEORETICAL BACKGROUND

The First Law of Thermodynamics has been used in order to study the quantity of energy in energy conversion processes. The energy balance of a control volume in steady-state steady-flow process, and neglecting the potential and kinetic energy changes, is given by Eq. 1 (Kotas 1995):

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} , \quad (1)$$

where \dot{Q} is the net heat rate, \dot{W} is the net power, \dot{m} is the mass flow rate, h is the specific enthalpy, the subscript *out* refers to the outlet stream, and the subscript *in* refers to the inlet stream. However, an energy balance shows only the distribution of the energy in quantitative terms – unlike the First Law of Thermodynamics, the Second Law illustrates, through exergy balances, the behavior of the quality of the energy in energy conversion process. Another advantage of the exergy analysis is its capability to identify potentials to improve the process performance by depicting the destroyed exergy sources. The exergy balance of a control volume in steady-state steady-flow process may be expressed by means of Eq. 2 (Kotas 1995):

$$\dot{B}_d = \sum_{in} \dot{B}_i - \sum_{out} \dot{B}_i + \sum \dot{B}^Q - \dot{W}, \quad (2)$$

where \dot{B}_d is the destroyed exergy flow rate, $\sum_{in} \dot{B}_i$ and $\sum_{out} \dot{B}_i$ are the sum of exergy flow rates of the streams i in the inlet and the outlet of the system, respectively, $\sum \dot{B}^Q$ is the sum of thermal exergies, and \dot{W} is the power in the control volume.

Table 1 presents some expressions for *energy efficiency* and *exergy efficiency* used in order to assess the performance of FPSO processes. As can be seen, there is not an energy efficiency expression to assess separation processes.

Table 1. Expressions for the energy and exergy efficiency of FPSO processes

	Separation	Compression	Gas turbine
ENERGY EFFICIENCY	–	$\eta_{comp} = \frac{\sum \dot{H}_{out} - \sum \dot{H}_{in}}{\dot{W}_{in}}$ \dot{H}_{out} : enthalpy flow rate of the outlet fluid \dot{H}_{in} : enthalpy flow rate of the inlet fluid \dot{W}_{in} : inlet power	$\eta_{GT} = \frac{\dot{W}_{net}}{\dot{m}_{fuel} \cdot LHV}$ \dot{W}_{net} : net output \dot{m}_{fuel} : mass flow rate of the fuel LHV : Lower heating value
EXERGY EFFICIENCY	$\eta_{B,S} = \frac{\Delta \dot{B}_{ch} + \sum_{out} \dot{B}_{ph}}{\sum_{in} \dot{B}_{ph} + \sum \dot{B}_H^Q + \dot{W}_{in}}$ $\Delta \dot{B}_{ch}$: chemical exergy increment \dot{B}_{ph} : physical exergy flow rate \dot{B}_H^Q : thermal exergy	$\eta_{B,comp} = \frac{\sum \dot{B}_{out} - \sum \dot{B}_{in}}{\dot{W}_{in}}$ \dot{B}_{out} : exergy flow rate of the outlet fluid \dot{B}_{in} : exergy flow rate of the inlet fluid	$\eta_{B,GT} = \frac{\dot{W}_{net}}{\dot{B}_{fuel}}$ \dot{B}_{fuel} : exergy flow rate of the fuel

In addition to *destroyed exergy* given in Eq. 2, *relative exergy destruction* for FPSO systems is calculated in order to identify the contribution of each FPSO system to total exergy destruction. *Relative exergy destruction* is given by the ratio between the destroyed exergy of system $\dot{B}_{d,i}$ and total destroyed exergy \dot{B}_d by the N systems in the FPSO (Kotas 1995):

$$1 = \sum_{i=1}^N \frac{\dot{B}_{d,i}}{\dot{B}_d} \quad (3)$$

Specific exergy destruction is another performance assessment criterion used in this paper. It is expressed as the ratio between the destroyed exergy in a system of the FPSO and the standard equivalent oil volume of the products of the FPSO. Separated oil for stock purposes and the exported gas are used to calculate the standard equivalent oil.

4. RESULTS AND DISCUSSION

Table 2 presents the simulation results of mass flow rate for the streams in the three operational modes shown in the Figures 1, 2 and 3. In accordance with the definition of each mode, the oil mass flow rate is higher in mode 3 than in modes 2 and 1, and mode 1 has higher water mass flow rate than modes 2 and 3. It may be noted that mode 3 has the highest gas mass flow rate and mode 2 has the lowest one, indicating that the gas content is not directly related with oil content in the three operational modes.

Table 2. Mass flow rates of the three operational modes

Stream	Mode 1 (maximum water/CO ₂)		Mode 2 (50% BSW)		Mode 3 (maximum oil/gas)	
	t/h	%	t/h	%	t/h	%
Crude	1219.2	-	1219.2	-	1219.2	-
Dilution water	9.8	-	24.4	-	48.8	-
Oil	180.6	14.7	453.7	36.5	921.6	72.7
Water	891.9	72.6	659.5	53.0	60.3	4.8
Gas (export)	-	-	34.8	2.8	257.2	20.3
Gas (injection)	156.6	12.7	65.2	5.2	-	-
Gas (fuel)	-	-	4.5	0.4	11.1	0.9
CO ₂ (injection)	-	-	25.8	2.1	17.8	1.4
Gas (imported fuel)	4.0	-	-	-	-	-

Temperatures and pressures for some streams in the FPSO are shown in Table 3. Pressures of gas and CO₂ injection processes are the highest of the overall process, while the lowest pressure in the FPSO process is found at the inlet of the VRU (outlet of the separation process). Conditions at the outlet of the MC-A system refer to the compressed gas after the cooling and dehydration process, as the discharge pressure from the main compressors is slightly greater. It can also be noted in this table that fuel gas properties in mode 1 (imported gas) have noticeable difference with those in modes 2 and 3 and the imported fuel comes in liquid phase. Export gas pressure is about half of the injection pressure.

Table 3. Temperature and pressure of the streams in the three operational modes

		Crude	Dilution water	Oil	Water	VRU (inlet)	MC-A (outlet)	Gas (export)	Gas (injection)	Gas (fuel)	CO ₂ (injection)
Mode 1	[°C]	20.0	26.0	62.4	20.2	40.0	40.0	-	40.0	5.0	-
	[kPa]	2300	705	383	2000	213	7895	-	49402	24517	-
Mode 2	[°C]	20.0	26.0	66.2	21.4	40.0	40.0	40.0	40.0	50.1	40.0
	[kPa]	2300	705	383	2000	213	7895	24998	49402	4752	49402
Mode 3	[°C]	20.0	26.0	67.5	23.5	40.0	40.0	39.9	-	56.8	40.0
	[kPa]	2300	705	383	2000	213	7895	24998	-	4752	49402

The total power consumption, heat requirement and thermal exergy use in the FPSO are presented in Table 4. The total power is the energy demand of the compressors and pumps used in the separation process. Thermal exergy (and heat) is used in the separation process to increase the temperature of the separated oil in the first stage, as well as to rise the temperature of the dilution water, maintaining a high temperature in the final separation stage. In addition, thermal exergy is used in the fuel gas system to reach a final gas temperature for the combustion process near 62 °C. According to this table, separation processes have the main demand of heat and thermal exergy in all operational modes in the FPSO. Mode 3 has the highest power demand, heat and thermal exergy requirements as a consequence of the highest oil and gas content in the crude oil implying more energy and exergy resources consumption for separation and compression processes, respectively; while mode 1 has the lowest requirements. Thermal exergy and heat requirements for the fuel heating are higher in the mode 1 than in the modes 2 and 3 because of the low temperature of the imported fuel.

Table 4. Total power consumption, heat and thermal exergy in the FPSO [kW]

Stream	Mode 1	Mode 2	Mode 3
	(maximum water/CO ₂)	(50% BSW)	(maximum oil/gas)
Power	14665	17766	43803
Heat used in separation process	6337	17146	39265
Heat used in fuel heating	432	90	169
Thermal exergy used in separation process	1500	4057	9293
Thermal exergy used in fuel heating	109	21	40

Table 5. Power consumption [kW] and **percentage** for FPSO systems

	Separation process		VRU		MC-A		MC-B				CO ₂ compression		CC			
							Injection		Export				Gas		CO ₂	
Mode 1	34	0.2	314	2.1	6283	42.8	5076	34.6	-	-	-	-	2959	20.2	-	-
Mode 2	86	0.5	788	4.4	7126	40.1	3057	17.2	2581	14.5	2176	12.2	1604	9.0	347	2.0
Mode 3	192	0.4	2048	4.7	19928	45.5	-	-	19886	45.4	1508	3.4	-	-	241	0.6

Power consumption in each FPSO system and its percentage of contribution in each operational mode are presented in Table 5. The power used in the separation processes corresponds to the energy consumed in the pumps used for water and oil recirculation. Consumed power in the separation process is the lowest for each operational mode, while the MC-A power consumption is the highest, nevertheless, in mode 3, MC-B has a power demand similar to the one consumed in the MC-A. The high power demand in mode 3 is associated with the high percentage of gas in the crude oil, and the low CO₂ content compared with modes 1 and 2, making it suitable for export purposes. The power consumption in the MC-B represents a significant part of the total power consumption in all operational modes, being about 8%-point lower than

the *MC-A* power consumption in modes 1 and 2. In the mode 2, the gas injection power requirement (power in *MC-B* section plus power in *CC* section) is more significant than the gas export power demand. In modes 2 and 3, CO₂ compression processes have low power demand compared with the total power consumption of the plant.

Tables 6 and 7 show the *destroyed exergy* and the *relative exergy destruction*, respectively, for the systems in each operational mode. The *GT* is the highest exergy destroyer system in all operational modes of the FPSO. The slightly higher destroyed exergy in *GT* in mode 1 vs. modes 2 and 3 is due to the irreversibility associated with the treatment of the imported fuel gas. Regardless the *GT*, the relative exergy destruction indicator shows that the main exergy destruction process in the processing plant is the *MC-A* in the mode 1, the separation process in the mode 2, and the *MC-B* in the mode 3. The destroyed exergy in the separation process is mainly related to the heating process of the crude oil. Additionally, pressure drops in the separators have a noticeable effect in the reduction of the physical exergy increasing the system irreversibility. In compression systems, gas cooling processes constitute the main source of exergy destruction. Compression processes related to gas injection and exportation purposes have a considerable effect in total destroyed exergy of three operational modes, and the sum of them has an relative exergy destruction higher than one in the separation process or the *MC-A*. On the contrary, exergy destruction of CO₂ compression processes does not notably affect the total destroyed exergy in FPSO modes. In mode 1, the relative exergy destruction in the separation process does not have a noticeable effect in comparison with those in *MC-A*, *MC-B* and *CC*. On the contrary, the relative exergy destruction of the separation process in mode 2 is higher than those calculated in the compression systems. In mode 3, the destroyed exergy is comparable with the irreversibilities in *MC-A*, *MC-B* and *CC*.

Taking into account the heat used in the separation process (in Table 4) and the power consumption (in Table 5), and comparing these results with those presented in Table 7 (without regard to *GT*), it is possible to conclude that:

- Mode 1: the results of energy consumption show that the first three energy consumers are, in descending order: the *MC-B*, the separation processes, and the *MC-A*; whereas the results of the relative exergy destruction (exergy analysis) show that the first three exergy destructors are: the *MC-A*, the *MC-B*, and the *CC*;
- Mode 2: the results of energy consumption and the relative exergy destruction indicate that the first three energy consumers are, in descending order: the separation process, the *MC-A*, and the injection section of the *MC-B*;
- Mode 3: the results of energy consumption show that the first three energy consumers are, in descending order: the separation process, the *MC-A*, and the injection section of the *MC-B*; whereas the results of the relative exergy destruction show that the first three exergy destructors are: the *MC-B*, the separation process, and the *MC-A*.

It may be noted that only in the mode 2, energy and exergy analyses coincide in the identification of the most energy and exergy relevant systems of the FPSO. In the modes 1 and 3, results about the energy and exergy relevance of the systems are different at least in order of priority.

Table 6. Destroyed exergy [kW] for FPSO systems

	Separation process	VRU	GDU	CO ₂ membrane	MC-A	MC-B		CO ₂ compression	CC		GT
						Injection	Export		Gas	CO ₂	
Mode 1	1353	83	915	-	2855	2055	-	-	1657	-	22729
Mode 2	4175	206	1095	418	3367	1278	1214	948	626	276	30692
Mode 3	9402	612	3387	1550	9174	-	9576	662	-	195	74577

Table 7. Relative exergy destruction for FPSO systems

	Separation process	VRU	GDU	CO ₂ membrane	MC-A	MC-B		CO ₂ compression	CC		GT
						Injection	Export		Gas	CO ₂	
Mode 1	4.3	0.3	2.9	-	9.0	6.5	-	-	5.2	-	71.8
Mode 2	9.4	0.5	2.5	0.9	7.6	2.9	2.7	2.1	1.4	0.6	69.3
Mode 3	8.6	0.6	3.1	1.4	8.4	-	8.8	0.6	-	0.2	68.3

Results of the specific exergy destruction expressed as MJ of destroyed exergy per standard cubic meters of equivalent oil are presented in Table 8. This indicator is useful to compare the performance of each system in the three operational modes. As can be seen from this table, in the separation process, mode 2 has the highest specific exergy destruction, and mode 1 has the lowest value, about 10% fewer. A noticeable difference may be observed in the specific exergy destruction for the *GDU*, *MC-A*, *MC-B* (injection section), *CC* (gas injection section), and *GT* in the mode 1, due its highest value in each system. This highlights that the mode 1, being the least power consumer and exergy destructor, is the most critical operational mode when the assessment parameter is the specific exergy destruction. Mode 3 has the lowest specific exergy destruction for FPSO systems (excepting the CO₂ compression and CO₂ section in the *CC*). Total specific exergy destruction for each operational mode is: 539 MJ/sm³ for the mode 1, 278 MJ/sm³ for the mode 2, and

286 MJ/sm³ for the mode 3. These findings suggest that, in the end- life of the field, the FPSO destroys the highest quantity of exergy to process the same quantity of oil and gas.

Table 8. Specific exergy destruction [MJ/sm³ of equivalent oil] for FPSO systems

	Separation process	VRU	GDU	CO ₂ membrane	MC-A	MC-B		CO ₂ compression	CC		GT
						Injection	Export		Gas	CO ₂	
Mode 1	23.1	1.4	15.6	-	48.7	35.0	-	-	28.2	-	387.5
Mode 2	26.2	1.3	6.9	2.6	21.1	8.0	7.6	5.9	3.9	1.7	192.5
Mode 3	24.7	1.6	8.9	4.1	24.1	-	25.1	1.7	-	0.5	195.6

The exergy efficiency of FPSO systems is presented in Table 9. *GT* has the lowest exergy efficiency in all operational modes. Irreversibilities occurring in the combustion process are the main source of destruction exergy in gas turbines. The energy efficiency of the gas turbine, on a LHV basis, was calculated as 29.3% for all operational modes. The separation process presents the highest exergy efficiency in mode 1 and the lowest in mode 2. This result does not allow for deriving any direct relation between the exergy efficiency and the crude oil composition. In compression systems, the exergy efficiency of compressors (which may be about 80%, see Table 10) is mainly affected by the gas cooling processes in the overall compression process, and the exergy efficiency may considerably vary depending on process conditions and the gas composition. For example, a noticeable difference is found for the exergy efficiency of the *CC* section for gas injection in modes 1 and 2. The inlet conditions for the two modes have a similar pressure (250 bar) but different temperatures (74 °C for mode 1 and 50 °C for mode 2 in order to have vapor condition), and the outlet conditions are identical (494 bar and 40 °C). These process conditions imply similar increase of the pressure-based/mechanical exergy but different reductions in temperature-based/thermal exergy, affecting in turn the exergy efficiency of the *CC*. In the same keynote, the *CC* section for CO₂ injection has a low efficiency for operational modes 2 and 3 as a consequence of the high inlet temperature of the CO₂ in the *CC*.

Table 9. Exergy efficiency of FPSO systems [%]

	Separation process	VRU	MC-A	MC-B		CO ₂ compression	CC		GT
				Injection	Export		Gas	CO ₂	
Mode 1	81.8	73.6	54.6	59.5	-	-	44.0	-	27.8
Mode 2	71.1	73.9	52.8	53.0	58.2	56.4	60.9	20.5	27.9
Mode 3	73.0	70.1	54.0	-	51.8	56.1	-	18.9	27.9

Exergy efficiency of FPSO compressors are presented in Table 10. As shown in this table, the *VRU*, and each section in *MC-B* have two compressors in series. CO₂ compression system has four compression stages. All compressors have exergy efficiency about 80% and adiabatic efficiency assumed as 75% for all machines. Slight variations in the exergy efficiencies are associated with differences in inlet and outlet temperatures and in the gas composition of the three operational modes.

Table 10. Exergy efficiency of FPSO compressors [%]. Adiabatic efficiency of compressors: 75%

	VRU		MC-A	MC-B				CO ₂ compression				CC	
	C1	C2		Injection		Export		C1	C2	C3	C4	Gas	CO ₂
Mode 1	79.8	80.2	82.0	79.1	79.9	-	-	-	-	-	-	80.9	-
Mode 2	79.1	79.5	82.0	83.0	80.1	81.0	80.1	82.0	81.6	81.7	79.9	79.5	81.7
Mode 3	78.5	79.2	81.8	-	-	81.4	80.2	82.4	81.6	81.7	79.9	-	81.8

5. CONCLUSIONS

Different indicators have been calculated for the three operational modes of a FPSO in order to assess the energy and the exergy performance of the systems. The ranking of the FPSO systems taking into account the power and heat requirements, establishing the priority from an energy point of view, is different from that one obtained when exergy criteria is applied.

Mode 3 has the highest power, heat and thermal exergy consumption, while mode 1 has the highest specific exergy destruction indicators for FPSO systems, which leads to conclude that the metric plays an important role in the FPSO assessment. This is the reason why the oil and gas industry suggests total and specific indicators.

Exergy performance indicators such as the destroyed exergy and relative exergy destruction were useful to identify the most critical systems in each FPSO operational mode. *MC-A* and *MC-B* systems were identified as relevant in the three operational modes. This identification is the first step in future work for the improvement of the processes and systems in the FPSO.

Specific exergy destruction has been a useful assessment criterion in order to compare similar systems for the three operational modes. Mode 1 has the most relevant values of this criterion compared with operational modes 2 and 3.

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7. REFERENCES

- Aspen Technology Inc. 2012. "Aspen HYSYS V8.0."
- Barrera, Julian Esteban, and Edson Bazzo. 2013. "Exergy Analysis and Strategies for the Waste Heat." In *22nd International Congress of Mechanical Engineering (COBEM 2013)*, 1674–82. Riberão Preto, Brazil.
- Barrera, Julian Esteban, Edson Bazzo, and Eduardo Kami. 2015. "Exergy Analysis and Energy Improvement of a Brazilian Fl Oating Oil Platform Using Organic Rankine Cycles." *Energy*. Elsevier Ltd, 1–13.
- Carranza Sánchez, Yamid Alberto, and Silvio de Oliveira Jr. 2015a. "Exergy Analysis of Offshore Primary Petroleum Processing Plant with CO₂ Capture." *Energy*. Article in Press.
- . 2015b. "Assessment of the Exergy Performance of a Floating, Production, Storage and Offloading (FPSO) Unit: Influence of Three Operational Modes." In *Proceedings of ECOS 2015 - the 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*. Pau - France.
- International association of oil and gas producers, and The global oil and gas industry association for environmental and social issues. 2013. *Guides for Implementing ISO 50001 Energy Management Systems in the Oil and Gas Industry*. <http://www.ogp.org.uk/pubs/482.pdf>.
- Kotas, T J. 1995. *The Exergy Method of Thermal Plant Analysis*. Florida: Krieger Publishing Company.
- Nguyen, Tuong-Van, Mari Voldsund, Brian Elmegaard, Ivar Ståle Ertesvåg, and Signe Kjelstrup. 2014. "On the Definition of Exergy Efficiencies for Petroleum Systems: Application to Offshore Oil and Gas Processing." *Energy* 73: 264–81.
- Nguyen, Tuong Van, Leonardo Pierobon, Brian Elmegaard, Fredrik Haglind, Peter Breuhaus, and Mari Voldsund. 2013. "Exergetic Assessment of Energy Systems on North Sea Oil and Gas Platforms." *Energy* 62: 23–36.
- Oliveira Jr, Silvio de, and Marco Van Hombeeck. 1997. "Exergy Analysis of Petroleum Separation Processes in Offshore Platforms." *Energy Conversion and Management* 38: 1577–84.
- Voldsund, Mari, Ivar Ståle Ertesvåg, Wei He, and Signe Kjelstrup. 2013. "Exergy Analysis of the Oil and Gas Processing on a North Sea Oil Platform a Real Production Day." *Energy* 55: 716–27.
- Voldsund, Mari, Tuong-Van Nguyen, Brian Elmegaard, Ivar S. Ertesvåg, Audun Røsørde, Knut Jøssang, and Signe Kjelstrup. 2014. "Exergy Destruction and Losses on Four North Sea Offshore Platforms: A Comparative Study of the Oil and Gas Processing Plants." *Energy* 74: 45–58.
- Voldsund, Mari, Tuong-Van Nguyen, Brian Elmegaard, Ivar Ståle Ertesvåg, Audun Røsørde, Knut Jøssang, and Signe Kjelstrup. 2013. "Comparative Study of the Sources of Exergy Destruction on Four North Sea Oil and Gas Platforms." In *Proceedings of ECOS 2013 - The 26th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, 2013*, 1–19.

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